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Research article

Paleoecological and historical data as an important tool in ecosystem management

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ABSTRACT

In recent decades, it has been observed that most forest fires in Europe were caused by people. Extreme droughts, which are more often prolonged, can increase the risk of forest fires, not only in southern Europe but also, in Central Europe. Nonetheless, catastrophic fire events are not well recognized in the Central European Lowlands (CEL), where large forest complexes are located. Knowledge of past fire activity in this part of Europe is scarce, although several fires have occurred in this area during the previous millennia. Large coniferous forest monocultures located in the CEL are highly susceptible to fires and other disturbances. Here, we present a case study from the Tuchola Pinewoods (TP; northern Poland), where large pine monocultures are present. The main aim of this study is to document the potential effects past land management has on modern day disturbance regimes using state-of-the-art paleoecological data, historical documents and cartographic materials. We then present a protocol that will help forest managers utilize long-term paleoecological records. Based on paleoecological investigations, historical documents, and cartographic materials, our results show that, in the past 300 years, the TP witnessed not only disastrous fires and but also windfalls by tornados and insect outbreaks. A change in management from Polish to Prussian/German in the 18th century led to the transformation of mixed forests into Scots pine monocultures with the purpose to allow better economic use of the forest. Those administrative decisions led to an ecosystem highly susceptible to disturbances. This article provides a critical review of past forest management as well as future research directions related to the impacts of fire risk on land management and ecosystem services: (a) habitat composition and structure (biodiversity); (b) natural water management; and (c) mitigation of climate changes. Designated forest conditions, management, and future fire risk are a controversial and highly debated topic of forest management by Forestry Units. More research will allow the gathering of reliable information pertinent to management practices with regard to the current fire risks. It is necessary to develop a dialog between scientists and managers to reduce the risk of fires in projected climate change.

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1. Introduction

In recent years, forests have become an important part of a number of scientific and political discussions – in particular, as an integral part of the climate change debate within the Paris COP 21 agreement – because trees accumulate carbon dioxide and can mitigate climate change (Kriegler et al., 2018; Seneviratne et al., 2018; Smith et al., 2018). Naudts et al. (2016) emphasize that as a result of the conversion of broadleaved to coniferous forests, the forests have changed into an environment with an increased carbon source. Forests surrounding peatlands are probably the only natural system that we can utilize to improve the efficiency of carbon dioxide accumulation (Seidl et al., 2014; Lamentowicz et al., 2016; Jassey et al., 2018; Kriegler et al., 2018; Seneviratne et al., 2018). Considering climate change with both positive and negative effects, we know that a "weak" (i.e., not resilient and not diverse) forest is primarily exposed to a greater number of threats posed by pathogens, diseases, and pests, and this is due to the overlapping of adverse weather conditions to fires (Johnstone et al., 2016; Kane et al., 2017; Ockendon et al., 2018).

Fire activity is well recognized in some of the European biomes. Weather conditions are a strong top–down driver of fire causes, whereas modifying drivers are topography and fire-promoting vegetation. Besides natural causes of fires – lightning, availability of dry fuel during dry hydrological conditions, or prolonged droughts – human activity is highly important. Approximately 8,000 years ago, Neolithic people began to transform the landscape of Europe, which at that time was almost entirely covered by forests (Vannière et al., 2011; Rey et al., 2013; Davis et al., 2014; Roberts et al., 2018). Furthermore, for example, Mediterranean vegetation was highly transformed by humans and is easily flammable (Colombaroli and Tinner, 2013; Sadori et al., 2013; Tinner et al., 2016; Morales-Molino et al., 2017). In contrast, Central Europe is not regarded as a flammable biome (Archibald et al., 2013; Dietze et al., 2018) and, therefore, not many studies have focused on the recognition of past fire activity in this area where big forest complexes along the Central European Lowlands (CEL) are located. There are a few records of fire available from Poland (Marcisz et al. 2015, 2017; Kajukalo et al., 2016; Latałowa et al., 2016; Słowiński et al., 2016), the Czech Republic (Adámek et al., 2016; Bobek et al., 2017; Dudová et al., 2017; Carter et al., 2018), Latvia (Feurdean et al., 2017), and Germany (Barber et al., 2004), but most of the available data are not analyzed in high resolution or using a contiguous sampling (Dietze et al., 2018). Published records suggest that humans actively used forest resources since the Subatlantic period (Adámek et al., 2016), however; the use of fire was only a local land management tool and large destructive fires were not recorded regularly. The map of the potential vegetation for this part of Europe suggests that, if this area was not modified by humans, it would be covered only to a small extent by fire-prone species and the forest composition would be dominated by a broadleaf mixed deciduous forest that rarely burns (Marquer et al., 2017; Roberts et al., 2018). The gradual perforation and fragmentation of forest complexes led to the deforestation of more than half of Europe (Davis et al., 2014). Deforestation was mostly destined for fields and pastures (Roberts et al., 2018), and human-induced fires were ignited to open the landscape for field formation and crop cultivation (Bowman et al., 2011). Land-use changes not only consisted of changing forest areas into open land-cover mosaic, but also of initially gradual, and then rapid, structural changes of the vegetation (Whitlock et al., 2018). Furthermore, accidental and uncontrolled ignition has been a common effect of anthropogenic activity thus far (Campos-Ruiz et al., 2018; Robinne et al., 2018). Because the use of forest complexes is administratively controlled, fires are sometimes caused as an effect of changes implemented in the ecosystem management plans (Butsic et al., 2015). Very often, management practices used in certain nature reserves are not adapted to ecosystem needs (Ockendon et al., 2018), as indicated by paleoecological studies and knowledge about ecosystem history (Lamentowicz et al., 2016).

Combining paleoecology with historical data allows us to better understand internal processes that occur in the studied ecosystems at various spatial and temporal scales (Colombaroli et al., 2017; Morales-Molino et al. 2017, 2018). Using multi-proxy approaches, we are able to better understand internal ecosystem relationships as well as their interactions with climate and human activity. Such knowledge allows us to prepare appropriate proposals for restoration and nature conservation by applying reference conditions for current landscape conditions (Battarbee et al., 2011a,b). Unfortunately, paleoecological and historical data on past vegetation and hydrological changes or fire activity that could be helpful in management (Saunders and Taffs, 2009; Birks, 2012; Hjelle et al., 2012; Whitlock et al., 2018) are often neglected when preparing management and nature conservation plans (Brown et al., 2018; Marcisz et al., 2018). The reasons are mainly an inefficient and ineffective communication between scientists and environmental managers, and that paleoecological expertise is time consuming and expensive (Hendon and Charman, 2004; Conedera et al., 2009; Aleman et al., 2018; Brown et al., 2018; Marcisz et al., 2018). However, there exist examples of how paleoeocological data can be used in the planning of forest management. For instance, Canadian studies from the boreal forest showed practical implications for management with the use of ecological land classification (Grondin et al., 2014), or a using partial cuts, irregular shelterwood system in order to avoid disturbances (Boucher and Grondin, 2012). In the Southern Alps, promotion of natural succession was suggested to maintain natural forest composition (Valsecchi et al., 2010). Historical fire regimes, plant flammability, fuel load, and data with regard to land-cover changes and anthropogenic influence should be considered in forest management and the design of more effective fire suppression strategies in the future (Harper et al., 2017; Law et al., 2018).

Here, we present a case study from the Tuchola Pinewoods (TP) located in northern Poland where the management of the forest has changed substantially since ca. 1700 CE due to political transformation and administrative changes. In a few years, a usage of the forest by local native people occupying small villages have been modified into a forest structured management system that was arbitrarily organized by a new Prussian administration. Those management changes led to a significant transformation in forest composition from mixed broadleaf-dominated forest to a Scots pine (*Pinus sylvestris* L.) monoculture. Our aim is to investigate how these changes in forest management influenced forest dynamics over the last 300 years based on palaeoecological investigations, historical documents and cartographic materials. The specific objectives are to: 1) show that in the past 300 years, as an effect of specific forest management, the Tuchola Pinewoods witnessed not only disastrous fires, but also windfalls by tornados and insect outbreaks; 2) provide a critical review of past forest management, as well as to draw suggestions for future research directions related to the impacts of fire risk on land management and ecosystem services, habitat composition and structure (biodiversity), natural water management,; and mitigation of climate changes.

2. Material and methods

2.1. Study area

The region of the Tuchola Pinewoods (TP) is one of the biggest pine forest complexes in Poland which covers ~3,000 km^2 (Giętkowski, 2008, 2009) (Fig. 1). The TP is located on the outwash plain of the Brda and Wda rivers formed during the Pomeranian phase during the last glacial period known as the Vistulian glacial period ~15.8 cal ka BP (Błaszkiewicz et al., 2015; Marks et al., 2015). The Brda and Wda form a typical polygenetic valley in young glacial areas (Błaszkiewicz et al., 2015; Słowiński et al., 2015) and are surrounded by a *Pinus sylvestris*-dominated forest. Brown forest podzolic soils developed on aeolian and glaciofluvial sands. This area is protected by Natura 2000 "Bory Tucholskie" (PLB220009) and "Wielki Sandr Brdy" (PLB220001) areas,

Fig. 1. Location of the study site: Czechowskie lake in the TP. The two comparison sites: Linje mire in the Chełmińske Lakeland and Rzecin mire in the Noteć Forest.

and by the "Bory Tucholskie" Biosphere Reserve. The local climate at the TP is characterized by a transitional climate that is influenced by continental and oceanic air masses (Woś, 1999). Annual rainfall averaged ~600 mm between 1981 and 1998. Annual temperatures averaged 7 °C, with January and July temperatures averaging -3 °C and 17 °C, respectively during the same time period (Kozłowska-Szczęsna, 1993; Wójcik and Marciniak, 1993).

Paleoecological investigations were based on sediments from Czechowskie lake, which developed in a subglacial channel in the outwash plain (Kordowski et al., 2015; Słowiński et al., 2017b) (Fig. 1). The lake is located in the northern part of the TP (53°52′27″N 18°14′12″E) at an elevation of 109.2 m a.s.l. and covers an area of 77 ha; the maximum water depth is 32 m.

2.2. Coring, paleoecological analyses, and historical and cartographical data

We used paleoecological, historical and cartographical data to reconstruct changes in forest composition in association with changing management strategies in the TP since ca. 1200 CE. For the paleoecological investigations, between 2009 and 2012, we collected four parallel and overlapping sediment sequences as well as short cores, using an UWITEC piston corer and a Ghilardi Gravity Corer (KGH 94) (Wulf et al., 2016; Ott et al., 2018). A chronology from Czechowskie lake was established using varve counting, AMS ^{14}C dating, ^{137}Cs activity concentration measurements, and tephrochronology (Czymzik et al., 2015; Ott et al. 2015, 2018; Wulf et al., 2016). The main core was sub-sampled for palynological analyses (sample volume: 1 cm^3) with 1–12 years resolution/sample to reconstruct past vegetation. Samples were prepared following standard methods (Fægri and Iversen, 1975), with the addition of *Lycopodium* tablets (Stockmarr, 1971) to estimate the pollen concentrations (grains/cm^3). The sum of pollen species indicating human activities was used to describe human activity over time, and includes the following taxa: *Humulus/Cannabis t., Cannabis sativa t., Triticum t., Secale cereale, Cerealia undiff., Scleranthus* sp., *Rumex acetosella, Plantago* sp., *Plantago major, Anthemis t., Artemisia, Chenopodiaceae, Urtica, Polygonum aviculare, Rumex acetosa t., Rumex acetosa/acetosella, Plantago lanceolata* and *Plantago media* (Behre, 1981; Poska et al., 2004).

In order to reconstruct past fire activity, microscopic charcoal analysis was conducted during pollen analysis. Microscopic charcoal particles > 10 μm were counted until the sum of 200 particles was reached (Finsinger and Tinner, 2005), which gives information about regional fires in an ~20–100 km radius from the study site (Vannière et al., 2008; Conedera et al., 2009). Then, we calculated the microscopic charcoal influx or accumulation rates (CHAR), expressed as charcoal particles/cm^2/year (Davis and Deevey, 1964). Paleoecological diagrams have been prepared in the Tilia/Tilia Graph software (Figs. 3 and 6) (Grimm, 1991).

We were able to access a large set of historical data documenting the management history of the TP since the 16th century, to which we refer to paleoecological results. Between the end of 18th century and the beginning of 20th century, Poland was occupied by Prussia, which implemented a new forest management. Old manuscripts documenting these administrative decisions were collected from the State Archive in Gdansk and Bydgoszcz. Cartographical data for the analysis of the scale and the direction of changes in the forest management were obtained from archives in Germany (Berlin State Library – Prussian Cultural Heritage and Secret State Archives - Prussian Cultural Heritage in Berlin) and Poland (State Archive in Gdańsk). Cartographical data (land-cover maps) to illustrate the changes in the forests area (Fig. 2). More detailed maps from the Borzechowo Forest Superintendence, where the Czechowskie lake is located, were used for comparison with paleoecological data (Fig. 2). The historical maps have been scanned in order to present them in the article (Fig. 2). Figures presenting potential vegetation have been prepared in CorelDraw Graphics Suite X8 based on CORINE Land Cover (present vegetation), potential vegetation by Matuszkiewicz (2008), and soil-type map 1:500,000 scale (Fig. 5). Photos of the sites have been gathered by the authors (Fig. 4A, D). The photos showing clear cuts in the TP and the Noteć Forest (i.e., a forest with similar history situated ~150 km southwest of TP) are based on Google Earth (Fig. 4B and C, Suppl. Fig. 1). Historical data have been used for comparisons and validation of palaeoecological analyses and we refer to them in the Discussion.

3. Results and interpretation of paleoecological investigations

Selected pollen taxa assemblages and microcharcoal influxes are used to reconstruct vegetation and regional fire histories (Fig. 3). As the article focuses on reconstruction of forest disturbances (such as insects outbreaks, risk fire or windthrows), we present our results following the main three fire phases.

3.1. Phase A (from ~1200 to ~1750 CE): stable fire conditions

Phase A was characterized by high percentages of arboreal pollen (~85%), with low values of pollen indicators of human activities. Drier habitats around Czechowskie lake were covered by forests dominated by *Pinus sylvestris*, *Quercus*, and *Carpinus betulus*, whereas wetter habitats where occupied by *Betula* and *Alnus*. Land-use changes were observed at the beginning of the 15th century and were associated with an increase in human activities in this region (increase from ~1.5% to ~12% in the sum of pollen indicators of human activities). Deciduous trees (mainly *Carpinus*, *Quercus*) gradually decreased from ~35% to ~5% by the end of the phase. CHAR values fluctuated, averaging ~1,500 particles/cm^2/year, and not exceeding 4,000 particles/cm^2/year.

3.2. Phase B (from ~1750 to ~1910 CE): pine monoculture and increased fire activity

During Phase B, pine increased (from ~40% to ~65%) with a simultaneous decrease in the arboreal pollen. Observed land-use changes were related to the increase in agricultural activities (sum of pollen indicators of human activities) but, mainly, with the change of forest

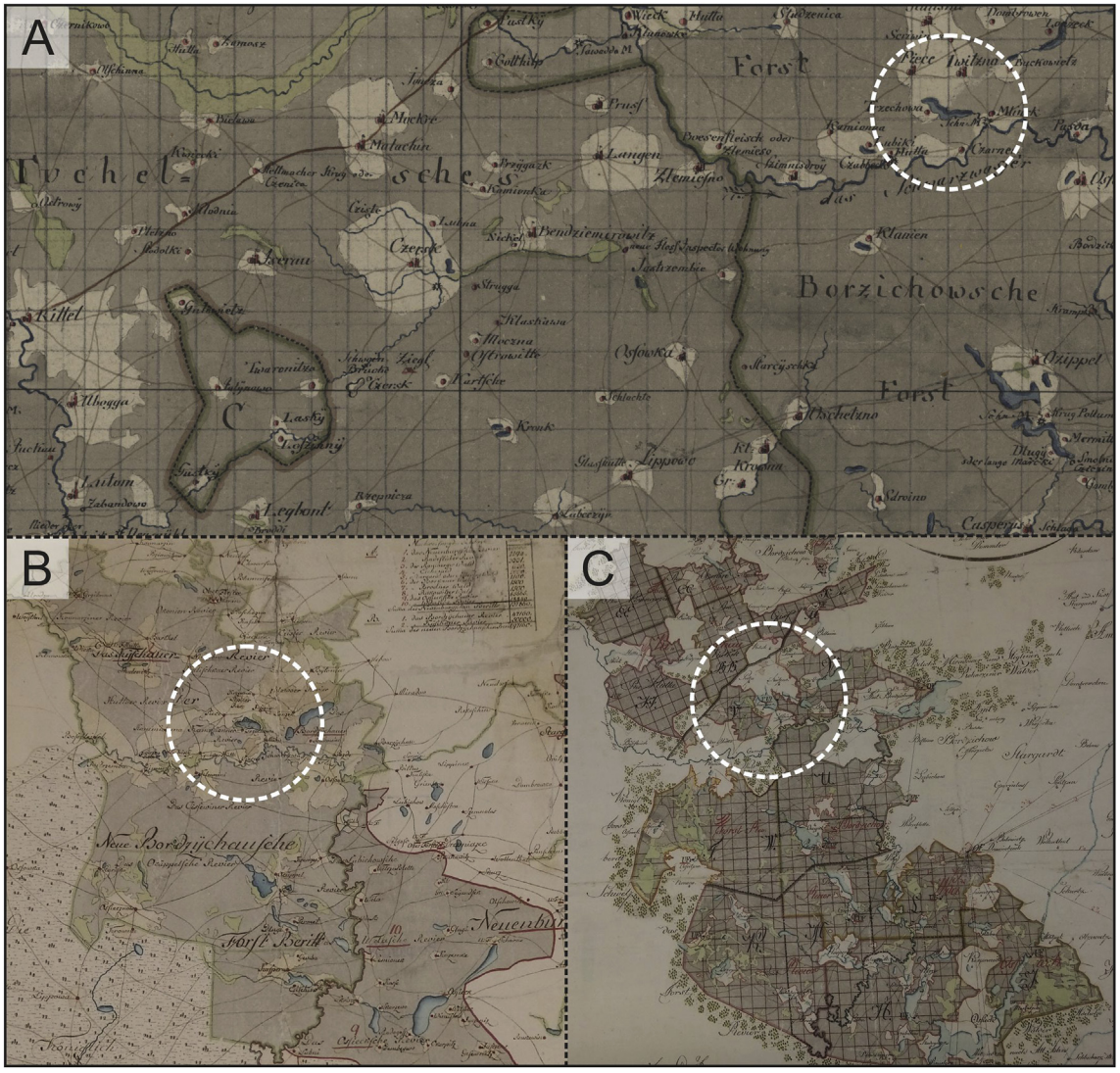

Fig. 2. TP on historical maps. (A) Densely forested area (dark gray) with small deforested enclaves (light gray) of the TP, (source: Karte von den Königl. Preuss. Provinzen Pommerellen und dem Netzdistrict (…), 1791–95, © Staatsbibliothek zu Berlin PK, Signature: IIIC Kart. N 12262 Blatt 4). (B & C) The area of the forest surrounding Czechowskie lake before (B) and after (C) the division to square frameworks, which was the first one of the main decisions of the new forest management in TP since end of 18th century. The division to square frameworks aimed mainly at improving forest management, such as trees cutting, improving transport conditions and controlling the spread of fires (source: B: Projektierte Teilung der Forst Neuenburg in die beiden Forstreviere Neuenburg und Neu Bordzichow, 1799, © Geheimes Staatsarchiv PK in Berlin, Signature: XI. HA, AKS, E 53585; C: Forste Neuenburg und Bordzichow, 1802, © Geheimes Staatsarchiv PK in Berlin, Signature: XI. HA, AKS, E 53380).

management. That change is accompanied by a sudden increase of CHAR values, with an average of ~3,100 particles/cm^2/year, reaching a maximum of 14,530 particles/cm^2/year in ~1860 CE.

3.3. Phase C (from ~1910 to 2010 CE): fire suppression and forest management

Phase C was characterized by a gradual afforestation of this area at the expense of agricultural areas (AP increase from ~55% to ~75%). We noted a small increase of deciduous trees (*Carpinus, Fraxinus, Quercus, Ulmus*), but the general increase in the share of AP is associated with the spread of pine. CHAR values averaged ~1,300 particles/cm^2/yr with a maximum at ~1950 CE when they reached 2,530 particles/cm^2/year. CHAR values have since decreased in the Czechowskie lake region.

4. Discussion

4.1. History of the forest, land-use changes, and administration and management in the Tuchola Pinewoods

Territorial affiliation has changed several times in the TP area, beginning in the 14th century. The first data documented by the historical sources indicate that the 14th century was a period of certification of the location of towns (medieval law of town privileges) in this area. Between 1308 CE and 1466 CE, Pomerania was under the rule of the State of the Teutonic Order; later, until 1772 CE, this area was under the rule of the Polish state. Until the mid-18th century, forests comprising oak, hornbeam, and other deciduous trees (*Fraxinus, Ulmus, Tilia, Fagus*) were mainly used as a source of bedding and a place for grazing cattle, sheep, swine, as well as for timber harvesting for living purposes, that is, building houses, firewood (Broda, 2000), similar to other forests in Central Europe (McGrath et al., 2015). Deforestation was carried out for the needs of beekeeping, glassworks, charcoal and

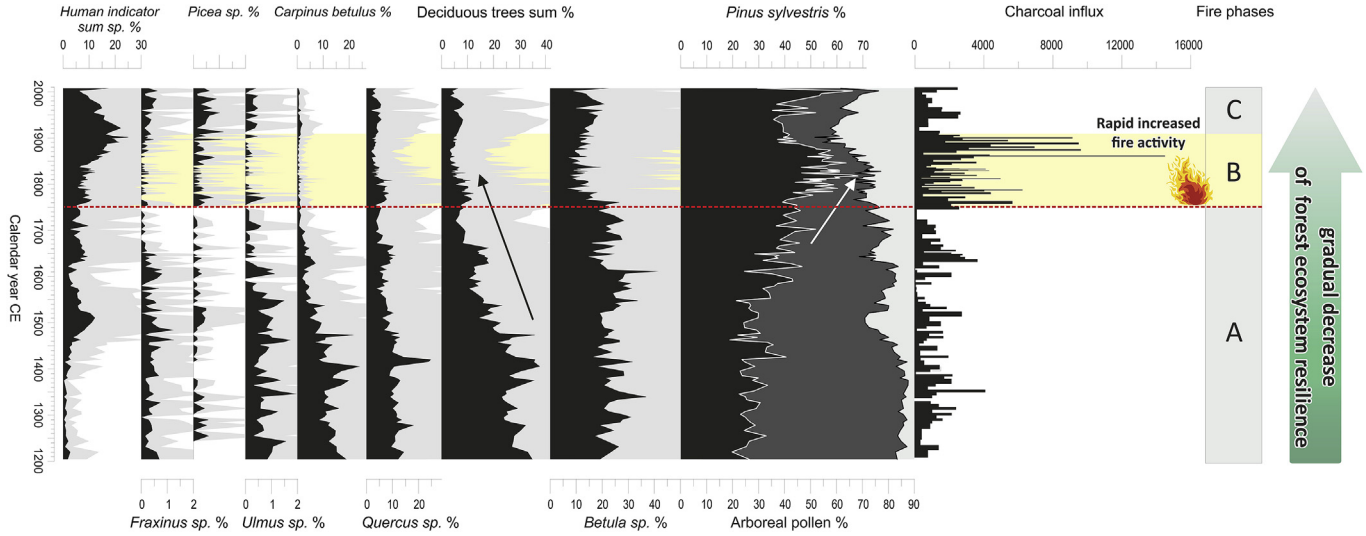

Fig. 3. Simplified pollen diagram from Czechowskie lake documenting the main tree species along with human pollen indictors, and microscopic charcoal (shown as influx; particles/cm^2/yr).

potash production logging, whereas was related to fragments of the forest complex with a predominance of deciduous trees (where oak and hornbeam together are > 35%) (Broda, 2000). Prior to the mid-18th century, it is difficult to assess the planned use of forest resources because areas subjected to deforestation were isolated islands located around emerging settlements and manufacturers using wood (e.g., sawmills) (Fig. 2). After the local forest resources were exhausted, deforested areas were adapted for agricultural purposes, as indicated by the increase in human indicator species. Settlements established prior to the 18th century were named after tree species exploited in the area: Cisiny (from yew; *Polish*: cis; *Latin*: *Taxus baccata* L.), Dąbrowa (from oak; *Polish*: dąb; *Latin*: *Quercus* L.), Bukowiec (from beech; *Polish*: buk; *Latin*: Fagus L.), Grabowo (from hornbeam; *Polish*: grab; *Latin*: *Carpinus* L.), Brzozie (from birch; *Polish*: brzoza; *Latin*: *Betula* L.), Osiek (from common aspen; *Polish*: topola osika; *Latin*: *Populus tremula* L.), and Wierzbiny (from willow; Polish: wierzba; Latin: Salix L.).

In the 18th century, areas covered with forests occupied ~30% of the then-Pomeranian Voivodeship of the Polish state, and the area of the TP covered ~530,000 ha (Biskup, 1974; Mikulski, 1994; Nyrek, 1997; Broda, 2000). The turning point in the history of forest management in this region was the moment of the first partition of Poland (1772 CE). TP which is part of area of Pomerania, was included in Prussia (Broda, 2000). As early as 1782, the Prussian King Fredrik issued a special order entitled “On the development of the Tuchola Forest”. Based on this order, eight administrative areas in the TP were created (covering ~6,000 ha each) (Jaszczak, 2008; Jażdżewski, 2008). To gain an idea about the acquired land, Prussians carried out detailed mapping of the Pomerania region. Using the maps, it was possible to plan the division of individual TP districts into sections for annual wood harvesting (Fig. 2C). The first projects of spatial division of the forest into square branches were made in 1790. Uniform and compact forest complexes of the TP have been divided by economic roads and branch lines. According to the edict of the Prussian government from 1799, measurements of all forest areas occupied during the partitions were carried out, taking into account their species composition and age, and the proposed size of deforestation and loads (Broda, 2000; Jaszczak, 2008; Jaszczak and Magnuski, 2010). In 1873, the first steam sawmill in the Bydgoszcz area was established on the Brda river estuary to process timber from the TP area. The deforestation process in the TP area started with great impetus and by the end of the 19th century, the TP region became the largest Prussian supplier of timber to the market. This transformation was reflected in the pollen record when deciduous trees decreased simultaneous to an increase in pine beginning in the 18th century. The increase in pine was a result of planted monocultures of this species. By 1893, more than 99% of forests in Tuchola County were planted with Scots Pine (Giętkowski, 2009; Ott et al., 2018). Additionally, the increase in pine pollen was accompanied by an abrupt increase in charcoal influx (Fig. 3). Since 1893, forest districts have not changed and this area is still covered by pinewoods. By 1913, there were already 20 large steam sawmills, which processed ~500,000 m^3 of hardwood a year and employed ~1,600 workers (Broda, 2000). At the turn of the 19th and 20th centuries, Prussian policy changed and areas previously used for agriculture were transformed into pine forests (Fig. 4A) (Szneider and Krysiak, 2014).

4.2. Forest fires recorded in paleoecological and historical data

Combined paleoecological and historical evidence gives an opportunity to better understand past relationships between humans and the environment, such as land-use changes, diseases, fire history, melioration, or vegetation composition. Historical data describing forest fires from before the 1830s should be treated with great care because these areas were not measured accurately (Schütte, 1893). Orłowicz (1924) emphasizes that only in the years 1794 and 1807 more than 34,000 ha of forests burned. However, an undeniable fact is that the occurrence of particularly large forest fires in the studied area in these years, as well as in subsequent years 1809, 1810, 1812, 1813 and 1828, is confirmed in written sources (Cyzman and Oleksik-Tusińska, 2008). The inference of increased fire activity at that time is supported by paleoecological investigations (rapid increase in CHAR; Fig. 3). In 1792, the city of Starogard, located in the northeastern part of the TP, was almost completely burned down with its surrounding areas (Orłowicz, 1924). Information about numerous fires in the Gdańsk region were documented in official Prussian diaries, especially since 1826. In 1843, 3,000 trees were logged in the Woziwoda Forest District after a significant fire. From 1850 to 1859 after several fires, 3,085 ha of forest was sowed and seeded (Orłowicz, 1924). This corresponds to the highest CHAR peak recorded in the Czechowskie lake record at 1859 CE (Fig. 3).

The most severe summer droughts occurred in the early 1860s (Schütte, 1893; Kirschenstein, 2005). In the summer of 1862, < 100 mm of rainfall was recorded, and four fires were observed in the Königsbruch and Wirty forest districts. Less than 50 mm of precipitation fell in the summer of 1863. As a consequence, once of the biggest fires occurred in the TP area; 1,276 ha burned in the Woziwoda Forest District at the end of August 1863. Another fire occurred on

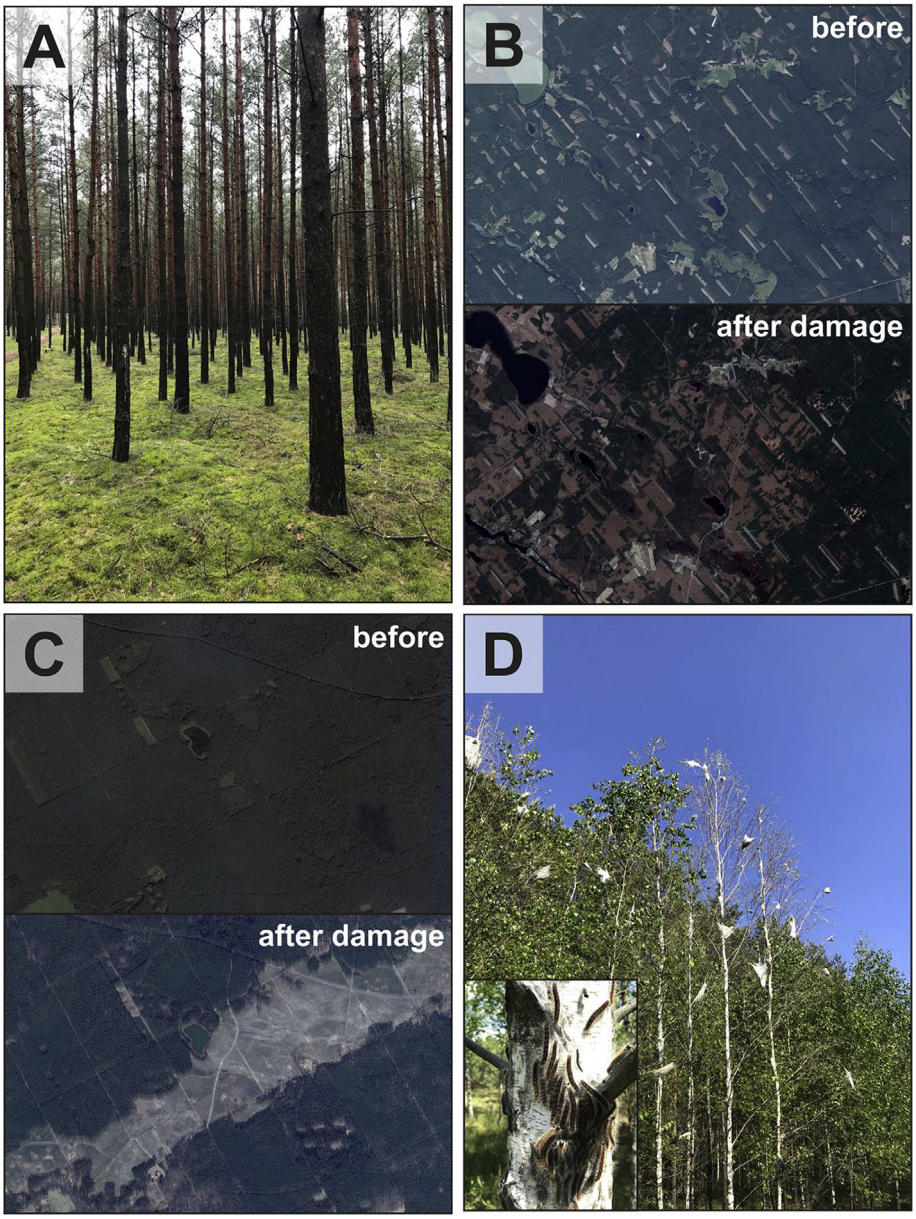

Fig. 4. Photos from the study region: (A) the pine monocultures of the TP with an example of the tree subjected in the past to resin extraction; (B) pine forest destroyed by strong winds in August 2017 in the Rytel district; (C) the impact of a tornado in 2012 on the TP; and (D) insect (*Eriogaster lanestris*) infestation of *Betula pendula* trees.

September 1 and burned an additional 70 ha in the Königsbruch district (Schütte, 1893). In the years 1860–1889, 310 fires were recorded in the TP, which destroyed more than 4,206 ha of forests (Orłowicz, 1924), which is strongly reflected in the CHAR record (Fig. 3). The largest fire was recorded in 1901 in the Taubenfließ (490 ha) and Junkerhof (173 ha) forest districts whereas, in 1910, 313 ha of forests in the Wildungen Forest District burned (Orłowicz, 1924). After World War II, only two forest fires were recorded. The first fire occurred on April 19, 1948 which was started by a locomotive spark on the Skórcz-Szlachta route near Osieczna. Firefighting continued for several days and ~450 ha of forest burned (Cherek, 2007). This particular fire was recorded in the Czechowskie lake record with a peak in CHAR at ~1948 (Fig. 3). The second fire occurred in 1954 when 80 ha of forest burned near Ocypel.

In the present day, fires observed in the TP are mostly ground fires, which are small and less intense (Archibald et al., 2013; Adolf et al., 2018), whereas crown burning is rarely observed. Most often, such fires appear in periods of prolonged drought and in early spring (most often, May), when the undergrowth has not yet greened (Karlikowski, 1975). Understorey and litter are the main fuel burned during ground fires, and the velocity of propagation of a fire depends mainly on the moisture content of the litter. Forest reports (Cyzman and Oleksik-Tusińska, 2008) show that particularly strong fires occurred in young pine stands (< 60 years) where *Calamagrostis*, *Calluna* and *Juniperus* comprise the understory (Agee, 1998; Adámek et al., 2016; Tepley et al., 2018). During early spring, and with long-term drought during the summer, fire spreads very quickly, and the low branch or understorey of *Juniperus communis* or *Picea abies* facilitate the transformation of the ground fire into a crown fire. In contrast to natural potential vegetation such as dense ferns or *Vaccinium* sp., there is limited spread of fire during the growing season (Cyzman and Oleksik-Tusińska, 2008).

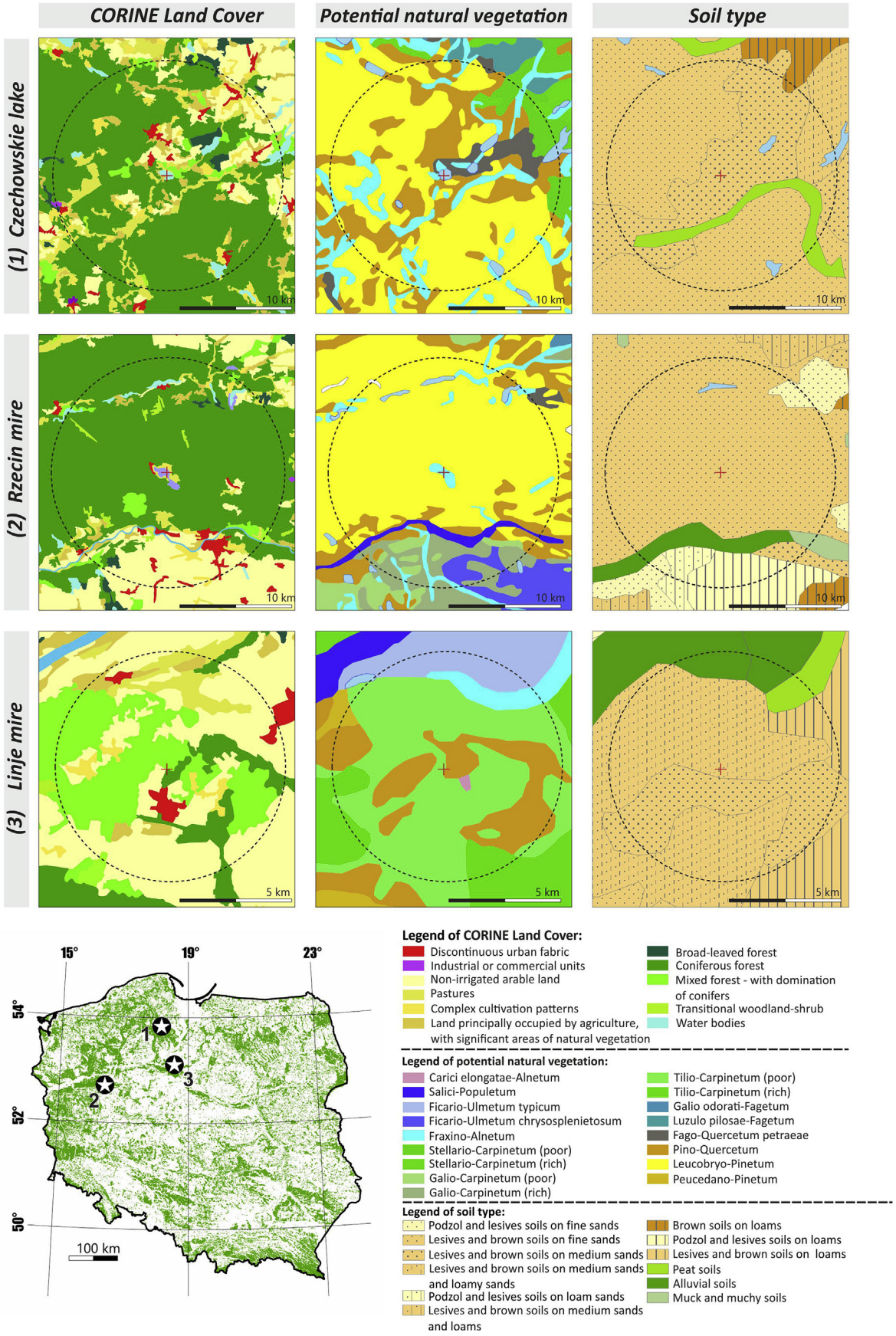

Fig. 5. Comparison of the selected key sites (Rzecin mire, Czechowskie lake, and Linje mire) in Poland showing potential vegetation (Matuszkiewicz, 2008), current vegetation (CORINE Land Cover), and soil-type maps.

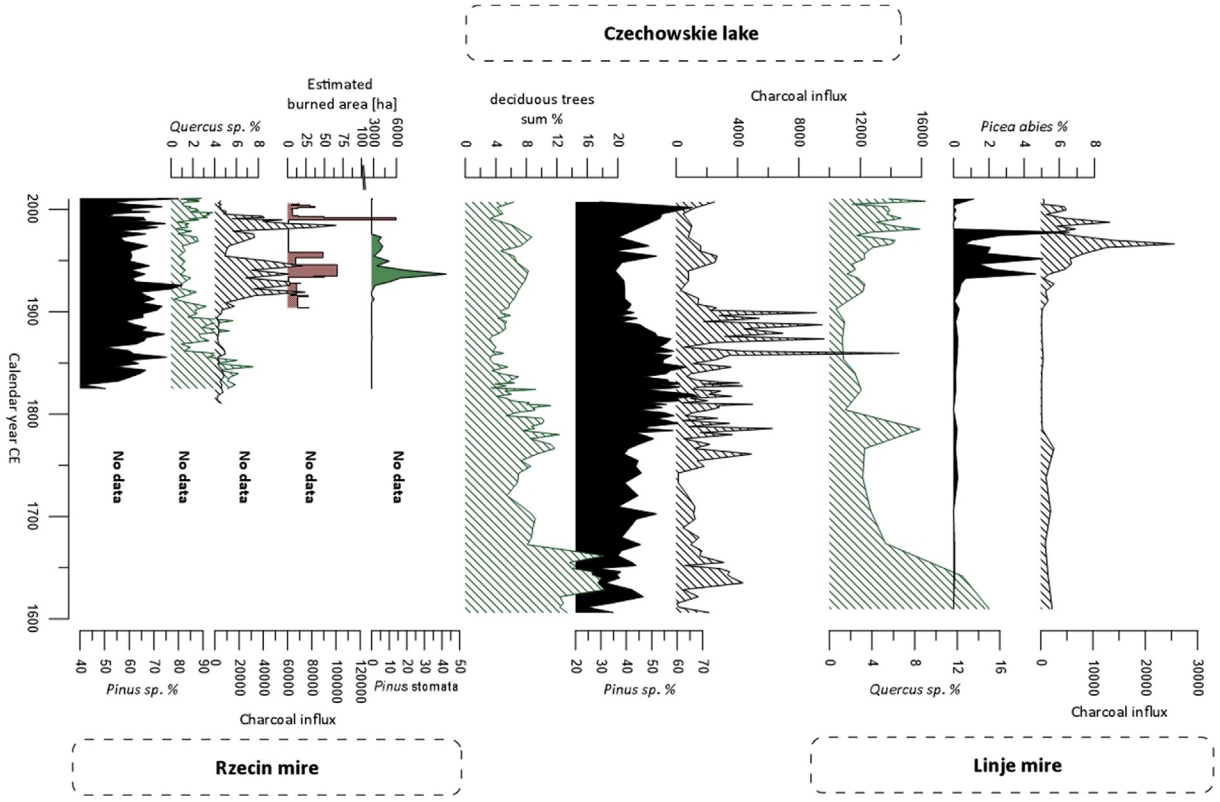

Fig. 6. Comparison of the selected key sites: Rzecin mire (Milecka et al., 2017), Czechowskie lake (Ott et al., 2018), and Linje mire (Marcisz et al., 2015) records showing coeval change of forest composition, land-use changes (pollen data), and fires (microscopic charcoal data). In the Rzecin record, the burned area has been estimated on the basis of historical data and crown fires have been recorded on the basis of the presence of the *Pinus* stomata in pollen samples.

4.3. Consequences of an inappropriate forest management and impact of recent climate change on fire-risk management across Poland

Forest ecosystems are characterized by a very complex system of mutual connections between the numerous organisms that create them; therefore, the loss of one link involves a whole chain of often hardly reversible events (Chapin et al., 2012). This relationship is not observed among forest monocultures (Cyzman and Oleksik-Tusińska, 2008). Chaudhary et al. (2016) emphasize that, historically, clear-cutting was the main type of forest management in the temperate and boreal biomes. This type of management is easy to execute and usually leads to monoculture (Greenberg et al., 1995; Rosenvald and Lõhmus, 2008; Fedrowitz et al., 2014). This type of management has been repeatedly criticized for various reason, specifically for simplifying vegetation structure and leading to homogeneous forests (Fig. 4A) (Gustafsson et al., 2012; Chaudhary et al., 2016). The management of forests and timber extraction causes local biodiversity losses and affects long-term resilience of forests (Gustafsson et al., 2012; Fedrowitz et al., 2014); likewise, by weakening the ecosystem (Lindenmayer et al. 2004, 2018; Huang et al., 2018; Mikusiński et al., 2018; Thorn et al., 2018), it ultimately reduces its services to the environment and human (Chaudhary et al., 2016). Clearcutting has a direct impact on the catchment area for abiotic components such as hydrological, hydrochemical, microclimatic, and soil processes (Sahin and Hall, 1996; Klimek et al., 2006; Ireland and Booth, 2012; Gandois et al., 2013; Woodward et al., 2014; Słowiński et al., 2017a). Over the years, the management of monocultures, in this case of pine, showed their low resilience and, consequently, multidimensional problems causing cascading consequences. Unfortunately, since the development of governmental forest management, monocultures were promoted because of financial constraints.

The TP is a good example of unsuitable forest management of low resilience. Until the beginning of the 18th century, this area was covered by a mixed forest with significant amounts of *Pinus* and broadleaf species such as *Carpinus, Fagus, Quercus, Tilia,* and *Populus* (Miotk-Szpiganowicz, 1992; Noryśkiewicz 2004, 2006; Milecka and Szeroczyńska, 2005; Lamentowicz et al., 2008) (Fig. 5). Due to drastic changes in forest management and the economy introduced in the 18th century (Broda, 2000), mixed forests have been turned into Scots pine (*Pinus sylvestris*) monocultures, with Scots pine dominating ~99% of forests in the area of the Tuchola County even today (Fig. 4A) (Giętkowski, 2009; Ott et al., 2018). Forest fragmentation with the use of fire was observed at that time in Linje mire, located in the Chełmińskie Lakeland ~120 km from the Czechowskie lake, where a drop in deciduous trees was noted due to an increased use of fire (Figs. 5 and 6) (Marcisz et al., 2015).

Similar management practices as in the TP have been undertaken in the Noteć Forest, western Poland (Figs. 5–6). The Noteć Forest (Figs. 1 and 5), located on the sandy dunes in the Toruń-Eberswalde ice-marginal valley formed during the Weichselian (Woldstedt, 1932; Pisarska-Jamroży, 2015), have been a mixed forests dominated by Pinus (~50–60%), and a combination of *Betula, Quercus, Tilia Corylus, Carpinus*, and *Alnus*. As recorded in historical data and in peat sediments from Rzecin mire (Figs. 5 and 6), deforestation started in the second half of the 19th century, and the Notec Forest was later afforested exclusively with Scots pine (Milecka et al., 2017). Currently, it forms a monoculture with 93% of trees being Scots pines with some silver birch mixed in (*Betula pendula*) (Łuców and Lamentowicz, 2015), and the forest is still exploited for timber with clear cuts (Suppl. Fig. 1). In all three study sites - Czechowskie Lake (TP), Linje and Rzecin mires, changes in forest management resulted in different vegetation composition from the potential natural vegetation typical for those regions (Fig. 5), with consequential disturbance regimes. Furthermore, in the Rzecin record, *Pinus* stomata were abundant in the 1930s, coinciding with outbreaks and moderate forest fires (Fig. 6). We believe that high

numbers of *Pinus* stomata may indicate insect outbreaks. After the needles fell down, they were partly decomposed and transported by the wind and run-off from the open surrounding dunes. Then, they could accumulate in the sediments and be preserved in the peat. In this way, stomata might be important proxies of insect outbreaks in paleoecological records.

The susceptibility to disturbances in monocultures is not only an effect of a strong domination of one tree species, but also is due to the subsequent management of these areas. In many cases, as well as in the case of the TP, forests are divided into subdivisions that are formed by trees planted within a short period of time, forming same-age forest stands (Grondin et al., 2014). These stands are easier to manage, include in economical plans, and perform efficient harvesting in clear cuts (Broda, 2000). However, such character of forest stands makes it easier for fires to spread or wind to put the trees down as has been emphasized by forest monoculture research (Van Wagner, 1977; Pretzsch et al., 2017; Liu et al., 2018). Unfavorable weather conditions and human activities often overlap, thereby triggering the development of fires. A very good example of this are the fires that occurred in August 1992 in Poland. The beginning of the nineties, namely 1990, 1991, and 1992, was characterized as very dry based on rain classification and, additionally, 1992 was an extremely warm year according to the thermal classification. Overlapping unfavorable climatic conditions, particularly very high temperatures (exceeding 30 °C) and the lack of significant precipitation, caused the development of fires in the areas of pine monocultures. The largest fire broke out in August 10, 1992 in several forestry districts in Southern Poland (Rudy Raciborskie, Rudziniec, and Kędzierzyn). Those fires were the largest fires in Central Europe after the Second World War (Dobrowolska, 2008) and it took 4 days and 10,000 people to put the fires out. At that time, a total of 9,062 ha of forest burned down and three people died. Another two large fires that also occurred in August 1992 were located in the area of Bory Dolnośląskie (southern Poland) and in the Noteć Forest (western Poland). In total, those fires burned nearly 20,000 ha of forests.

Moreover, similarly as other pine monocultures in Poland, the TP witnessed further insect outbreaks (*Panolis flammea* and *Lymantria monacha*) in the 20th century (Kannenberga and Szramki, 2008; Milecka et al., 2017). A unified forest composition or the high domination of one tree species is hazardous in terms of beetle infestations. Monocultures are more susceptible to insect outbreaks than mixed forests because it is easier for insects to spread from tree to tree and quickly attack the whole tree stand (Soja et al., 2007; Kurz et al., 2008; Jactel et al., 2009; Turetsky et al., 2012). It has been shown that wildfires often co-occur with insect outbreaks (Seidl et al., 2014; Mietkiewicz and Kulakowski, 2016) because they both have a common climatic driver (Mietkiewicz and Kulakowski, 2016). For example, the Rzecin mire (Noteć Forest) fires in the 1920s and 1930s coincided with the outbreak of *Panolis flammea*, a species that almost exclusively feeds on *Pinus sylvestris*, in 1922–1924 (Fig. 6) (Milecka et al., 2017) (Kiełczewski, 1947). A study from Engelmann spruce forests in the Wasatch Plateau in central Utah, USA, showed that after the forests under a dynamic fire regime were affected by anthropogenic logging, simplified stand structure became less resistant and more susceptible to disturbances, which resulted in severe spruce beetle outbreaks that killed more than 90% of mature spruce in the area (Morris et al., 2015). Changes in climatic conditions can increase the vulnerability of forests to increasingly extreme weather conditions. In connection with warmer and drier spring and summers, an increase European spruce bark beetle (*Ips typographus*) outbreaks can occur, which can increase its population many times (Wermelinger, 2004; Grodzki, 2016; Morris et al., 2018). The Białowieża Primeval Forest is a good example where mass outbreaks of the spruce bark beetle have been observed (Kujawa et al., 2016; Stokstad, 2017; Żmihorski et al., 2018), and they are related to many overlapping ecological factors and mechanisms (Faliński, 1986; Keczyński, 2005; Czerepko, 2008; Kuijper et al., 2010; Niklasson et al., 2010; Bobiec, 2012; Bobiec and Bobiec, 2012). New detailed analysis shows a 26% increase in fragmentation in the entire Natura 2000 area of the Białowieża Forest as a result of logging by the State Forest department while removing dead spruce (Mikusiński et al., 2018). Latałowa et al. (2016), showed that spruce pollen percentages in the Białowieża Primeval Forest were characterized by significant short- and long-term fluctuations which may be linked to beetle outbreaks in the past millennium.

In addition, the 20th century the Polish State Forest policy was centered on the planting of pine monoculture that, on the one hand, allowed them to make quick profits but, on the other hand, the stands were prone to further disturbances. In the 21st century, the TP were partly destroyed by extreme weather events. On July 14, 2012, a tornado destroyed 550 ha of forests in the Trzebciny Forest District (part of the TP), (Fig. 4C) (Słowiński et al., 2017a). On August 11 and 12, 2017 a storm destroyed 8 and 6 ha of forests in the Rytel and Lipusz districts (part of the TP), respectively, and five people died (Fig. 4B) (Fronczak, 2017). The storm in 2017 removed trees that were equal to 20–25 years of timber supply that was planned to be acquired from the forest, adding up to a damaged area of nearly 80,000 ha. Such disastrous disturbances and catastrophes progress quickly in monocultures; therefore, interventions based on paleoecological evidences (Marcisz et al. 2015, 2017) and the inclusion of climate change scenarios in forest management will help to not only fight wildfires, but also to minimize risks of further disturbances (Fig. 7) such as insect outbreaks (Mietkiewicz and Kulakowski, 2016).

Observation and predictions show the area of the central Europe as being susceptible to changes of climate, which is manifested by instability and more often extreme events such as prolonged heat waves, droughts and hydrological extremes (Hov et al., 2013; Romanowicz et al., 2016; Mezghani et al., 2017; Pińskwar et al., 2018). Hanninen (2006) emphasizes that the weakness in these regions will be associated with milder winters, which may reduce winter hardening in trees, increasing their vulnerability to frost. The projected increase in air temperature together with prolonged droughts will strongly impact insect population dynamics and distribution, and trigger outbreaks of certain pests (Wermelinger, 2004; Hlasny and Turcany, 2009). Insect outbreaks will benefit from a fully developed second generation of bark beetles (e.g. *I. typographus*) as noted in 2015 in the Slovakian forest (Wermelinger, 2004; Hlasny and Turcany, 2009). Balci and Halmschlager (2003) mention that, during prolonged droughts, trees are exposed to the development of fungal pathogens (e.g. Oak, *Phytophthora quercina*).

Unfortunately, many decisions made in the past have irreversibly changed the hydrology of wetlands in forest areas, weakening the forest stands. Between 1951 and 1991, 845,495 ha of wetlands were drained by the Polish Forestry (Wiśniwski, 1996). The drainage of wetlands not only reduces biodiversity, but also makes the forest more susceptible to the effects of drought, decreasing forest resistance against fires (Joosten and Clarke, 2002; Erwin, 2009; Mansuy et al., 2010; Smirnova et al., 2017; Robinne et al., 2018).

Monocultures are more susceptible to fire, especially if they are composed of fire-prone species (Felton et al., 2016). Therefore, forest managers and foresters should promote forests with more diverse species composition (mixed forest) in order to suppress the spread of not only fire, but also other forest disturbances such as insects outbreaks (Jactel and Brockerhoff, 2007; Bielak et al., 2014). Bark beetle outbreaks have been commonly observed in the 20th century (Morris et al., 2016), and may be more frequent together with progressing climate changes (Marini et al., 2017; Seidl et al., 2017b; Morris et al., 2018). Therefore, it is recommended to change monocultures in the future toward a potential natural vegetation (mixed forest). Naturally, in the climatic zone and biome in which Poland is located, forests should be dominated by temperate broadleaf and mixed forest species, and those types of forest are most resistant and resilient to fires (Lindner et al., 2010). When changes in forest stands would be implemented, even with an admixture of the share of the deciduous stand, it would make the

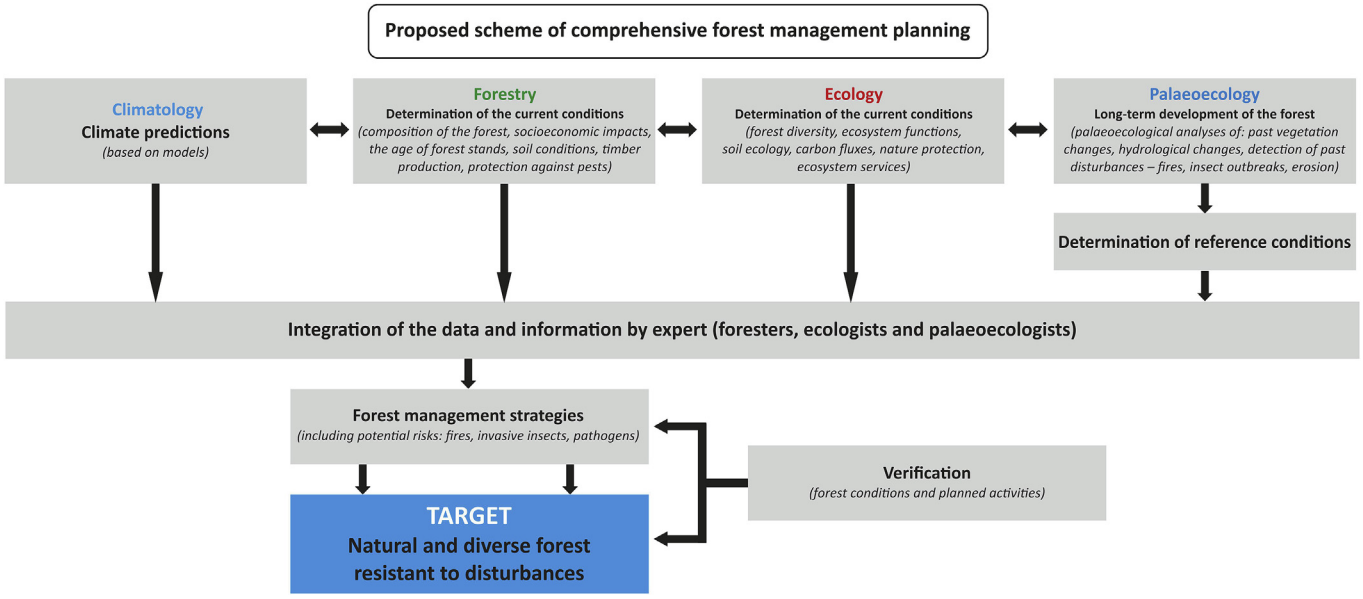
Proposed scheme of comprehensive forest management planning
Climatology
Climate predictions
(based on models)
Forestry
Determination of the current conditions
(composition of the forest, socioeconomic impacts, the age of forest stands, soil conditions, timber production, protection against pests)
Ecology
Determination of the current conditions
(forest diversity, ecosystem functions, soil ecology, carbon fluxes, nature protection, ecosystem services)
Palaeoecology
Long-term development of the forest
(palaeoecological analyses of: past vegetation changes, hydrological changes, detection of past disturbances – fires, insect outbreaks, erosion)
Determination of reference conditions
Integration of the data and information by expert (foresters, ecologists and palaeoecologists)
Forest management strategies
(including potential risks: fires, invasive insects, pathogens)
Verification
(forest conditions and planned activities)
TARGET
Natural and diverse forest resistant to disturbances

Fig. 7. Proposed scheme of comprehensive forest management planning (paleoecology, conservation strategies, description of landscape condition, knowledge of long-term ecosystem dynamics, land-use changes, and climate history). Finial recommendation should be based on the opinion of specialists. Primary information should come from paleoecology to inform about past land use and determine reference conditions of certain ecosystems. Then, the result should be compared with the knowledge about ecology and forest conditions, climate predictions, and, finally, with conservation strategies to do with forest management strategy.

entire ecosystem more resistant to further disturbances (Cyzman and Oleksik-Tusińska, 2008; Seidl et al., 2017a).

5. Conclusion

As far as European forests are concerned, we are currently facing a number of challenges, including loss of habitats (Sabatini et al., 2018), greater risks associated with encroachment of invasive species (Walther et al., 2009; Butchart et al., 2010), pollution (Bytnerowicz et al., 2007; Vuorenmaa et al., 2018), climate change (Bytnerowicz et al., 2007; Lindner et al., 2010; Seidl et al., 2017b), pathogens (La Porta et al., 2008; Santini et al., 2013; Stivrins et al., 2017), and fire risk (Pereira et al., 2016; Harper et al., 2017; Francos et al., 2018). Therefore, forest managers and foresters should promote forests with more diverse species composition (mixed forest) in order to suppress fire, but also other forest disturbances, such as insects outbreaks or windthrows (Jactel and Brockerhoff, 2007; Bielak et al., 2014).

As shown by our example from the TP, paleoecological data are a valuable source of information regarding past environmental change because they generally overlap with historical data, often confirming historical information, as well as provide information spanning longer timescales (Noryśkiewicz, 1999; Milecka and Szeroczyńska, 2005; Lamentowicz et al., 2007; Apolinarska et al., 2012; Ott et al., 2018; Słowiński et al., 2018; Zawisza et al., 2019). Therefore, they should be taken into account during the planning of forest management. Moreover, paleoecological data can be advantageous in the places where no such historical data exist or were lost due to various reasons.

Management focused only on future financial benefit may have a destructive consequence for the ecosystem. Planning by ecosystem managers who do not know the ecosystem well may be effective and financially successful only in the short term and disastrous in the long-term perspective. Therefore, long-term planning is especially important to use the resources wisely. We want to emphasize that the mosaic of relationships and dynamics, which are characterized by ecosystems of overlapping and constantly changing components (soil, hydrology, microclimate, and vegetation) that occur in the natural environment vary between different types of forests and should be treated with caution (Figs. 5 and 7). Therefore, reference conditions for ecological restoration should not be construed as a fixed set recipe for ecosystem management. We suggest that restoration works should be supported by earlier paleoecological studies to determine the appropriate reference conditions (Marcisz et al., 2018). Thus, paleoecological studies are crucial when producing management plans for not only forest complexes, but also for other ecosystems (Fig. 7).

Authors contribution

Idea of this study was developed by MS and KM. Interpreted the data with the assistance of all authors who contributed with discussions and text. The text was written by MS and KM and edited by all authors.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jenvman.2019.02.002.

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